STATE OF ARIZONA
DEPARTMENT OF WATER RESOURCES

INITIAL TESTING OF AN ULTRASONIC TRANSIENT - TIME FLOWMETER USING THE ADWR METHOD FOR MEASURING WATER FLOWS IN CARBON-STEEL PIPES

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CONTENTS

ILLUSTRATIONS

TABLES

INITIAL TESTING OF AN ULTRASONIC TRANSIENT-TIME FLOWMETER USING THE ADWR METHOD FOR MEASURING WATER FLOWS IN CARBON-STEEL PIPES

By

B. A. Hammett

INTRODUCTION

The Compliance Field Unit of the Arizona Department of Water Resources' (ADWR) Basic Data Section tested a portable ultrasonic transient-time flowmeter during the first half of 1986. The flowmeter is designed to measure flows in a pipe of specific material, thickness, and diameter. Plug-in scale modules program the flowmeter's computer to calculate flow, in units requested by the equipment purchaser, for a specific pipe when used with properly matched transducers.

Analysis of and field experimentation with the flowmeter led to what is herein described as the "ADWR method" for using this equipment to measure flows in pipes of different materials, thicknesses, and diameters. The ADWR method involves use of a spacing formula for transducer placement on non-design sized pipes and a coefficient, based on pipe-area ratio, for converting flowmeter readings to actual flow values. This greatly expands the utility of a scale module. The Compliance Field Unit has used two scale modules to measure flows in the field in pipes ranging in diameter from six inches nominal to fifteen inches nominal, and ranging in thickness from about one-tenth inch to more than one-half inch. Testing has so far been limited to carbon-steel pipes.

The purpose of this report is to describe the use of the ADWR method with the ultrasonic flowmeter, and to present the results of its testing in two laboratory situations. Limitations of the method and the equipment are discussed and recommendations made for further research.

BACKGROUND

The Arizona Groundwater Management Act of 1980 established requirements for owners/operators of "non-exempt" wells with regards to measuring flow rates and reporting annual groundwater withdrawals. Non-exempt wells include essentially all wells, except those for domestic use with pumping capacities of thirty-five gallons per minute or less, within the active management areas and irrigation non-expansion areas of the State (fig. 1). Among the requirements is that pumped groundwater must be measured by a device meeting a flow-rate accuracy of ±10 percent as measured at the wellhead. The Compliance Field Unit is charged with collecting well flow-rate measurements and related data used to monitor compliance with the Groundwater Code.

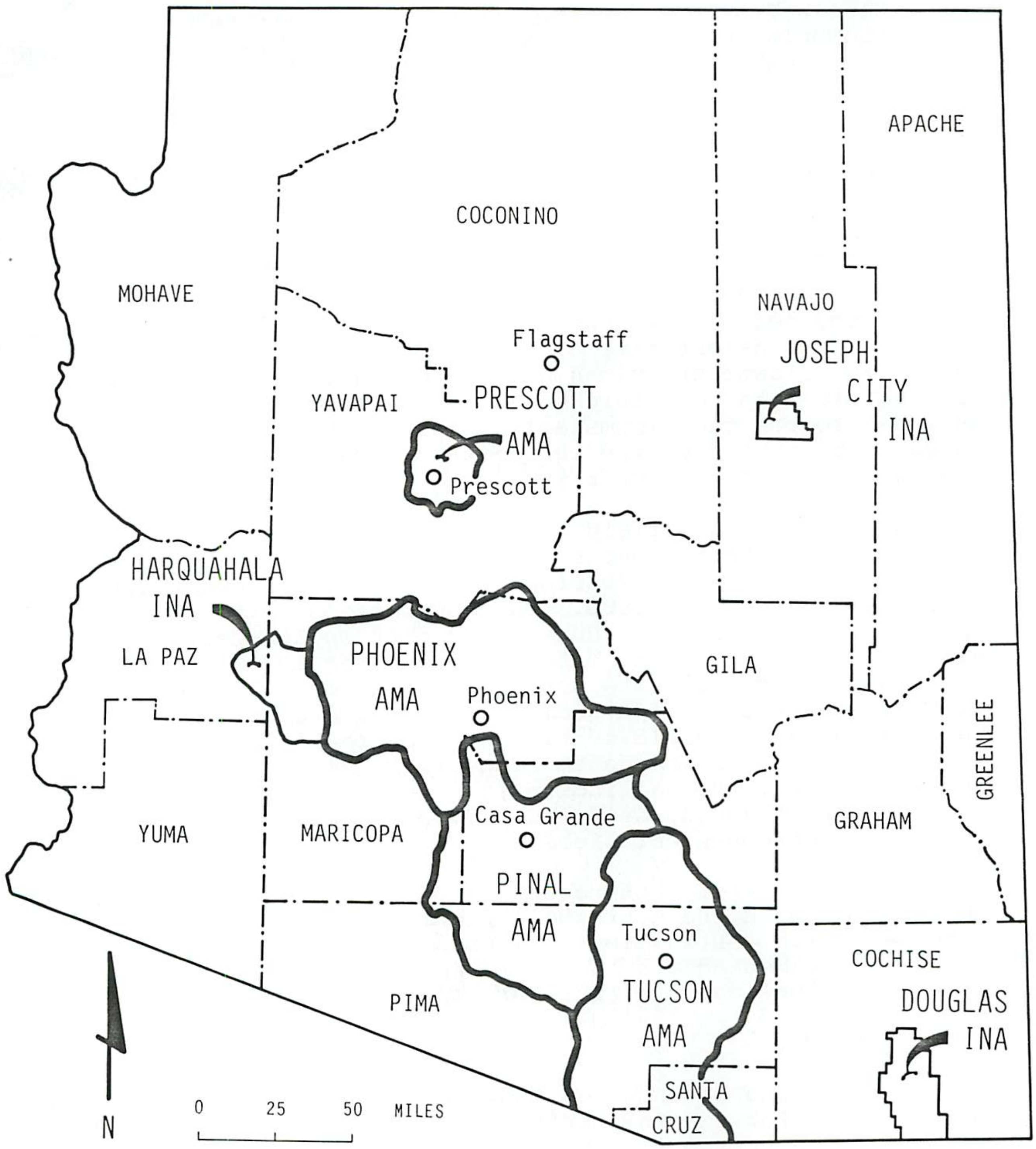


Figure 1.--Active management areas and irrigation non-expansion areas of Arizona, 1986.

The Compliance Field Unit employs several instruments for measuring well-flow rates. These include pitot tubes, weirs, current meters, and volumetric devices. During the winter of 1984-85, a Series 480 Clamp-On Flowmeter which is designed, built, and marketed by Controlotron, Inc.,[1] of Hauppauge, New York, was leased from the U.S. Geological Survey's Hydrologic Instrumentation Facility (HIF). This portable ultrasonic transient-time flowmeter appeared to be potentially useful for measuring flows in high-pressure systems, since invasion of the pipe wall is not required. HIF had developed linear equations from laboratory water-flow data for various combinations of scale modules and transducers on pipes of differing dimensions and materials. These equations permit translation of computer readings to gallons per minute flow rate. However, accuracy is sacrificed as pipe dimensions encountered in the field differ from those of pipes tested in the laboratory. The leased equipment included two scale modules with accompanying equations for pipes ranging from six inches nominal to twelve inches nominal. Field testing of this equipment led to the Department purchasing identical equipment in late 1985.

Data collection commenced using the new equipment in February 1986. Analysis of the data collected in February and March suggested that a more precise method than use of the HIF equations was possible for translating the computer readouts to flow rates, if a proper transducer-spacing formula could be developed. Limited to comparisons with in-line flowmeters in the field, several spacing formulas were tested. Appendix A presents the derivation of the formula finally developed which allows translation of readouts to flow rates with multiplication by the ratio of the inside area of the pipe being measured to the inside area of the pipe for which the scale module was programmed.

Field data collected in early 1986 using the ADWR method are presented in Appendix B. These data show high agreement between flow readings with the ultrasonic flowmeter and the in-line flowmeters. In late April, tests under more controlled conditions were run at the U.S. Department of Agriculture's Water Conservation Laboratory in Phoenix, and in June at the Foundation for Cross-Connection Control and Hydraulic Research Laboratory in Glendale, California. The results of these tests demonstrate that the ADWR method yields accurate results under laboratory conditions. However, a problem was encountered in the latter laboratory which had been indicated at times earlier in the field. The problem is probably specific to the equipment purchased by the Department, and seems to be electronic in nature. This will be described subsequently.

[1] Use of brand names in this report is for identification purposes only and does not imply endorsement by the Arizona Department of Water Resources.

DESCRIPTION OF EQUIPMENT

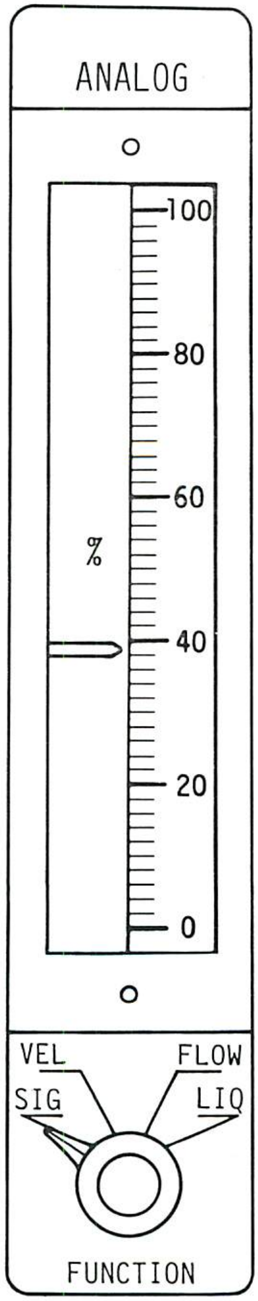
The equipment is pictured in figure 2 as installed on a typical discharge pipe. It includes the basic computer (left), two scale modules (inserted in the computer), two transducers (strapped on the pipe), and a pipe-thickness gage (right foreground). The pipe-thickness gage is not a part of the flowmeter, but is used to determine the average thickness of pipe in which the flow rate is to be measured. Mounting tracks (not shown) are a standard component of the flowmeter when it is used according to the manufacturer's directions. However, straps are more useful for securing the transducers when the ADWR method is used. The mounting tracks were used to develop the transducer-spacing formula essential to the ADWR method (Appendix A).

The basic computer is Controlotron's Model 484 MP Flow Display Computer. Among its major output features is a 4-digit instantaneous flow-rate/direction display. A high-low switch allows readings in the velocity ranges of ±40 feet per second or ±4 feet per second, again when the unit is used according to the manufacturer. A mechanical totalizer display has 6 digits zeroed with a reset button, and is scaled to 1, 10 or 100 units with a multiplier selection switch. An analog display is controlled by a function selection switch. When the unit is used to measure flow rates of liquids with different sonic velocities in pipes of the same dimensions (and all other components properly matched) the analog-display functions provide voltage readings proportional to receive-signal amplitude (V_{ALC}), liquid-flow velocity (V_{OF}), liquid-sonic velocity (V_{TL}), and percent of maximum flow (V_O) (fig. 3). It is not within the scope of this report to discuss the theory of how the readouts are altered when the ADWR method is used. However, with the ADWR method, V_{OF} is proportional to water-flow velocity, and V_{TL} appears to be approximately proportional to the inside diameter of the pipe being measured.

The plug-in programs are 484 Scale Modules. One module programs the computer to calculate flows in a 6.625-inch outside diameter carbon-steel pipe with a thickness of .231 inches. The other module programs the computer to calculate flows in an 8.625-inch outside diameter carbon-steel pipe with a thickness of .231 inches. The 481 P-CS5.78 transducers are designed for a pipe-wall thickness matching the scale modules. The 484 MT tracks are scaled for use with the 8.625CS.231 scale module. The final components of the flowmeter are the 482C cables which connect the transducers to the computer. The pipe-thickness gage is a Comparagage CG1 Pipe Thickness Indicator with a TMP-1 transducer, manufactured by Balteau Sonatest in Great Britain.

The late 1985 cost for the flow-display computer and the various components was approximately $9,000. The cost of the pipe-thickness gage was approximately $2,500.

Figure 2.--Ultrasonic transient-time flowmeter components and pipe-thickness gage.



Analog readout quantity	Function selector	Analog voltage
Receive-signal amplitude	SIG	V_{ALC}
Liquid-flow velocity	VEL	V_{OF}
Percent of maximum flow	FLOW	V_{O}
Liquid-sonic velocity	LIQ	V_{TL}

Figure 3.--Schematic of analog display and function selector.

ADWR METHOD SET-UP PROCEDURES[2]

The flowmeter requires a 50-watt, 105-122 volt AC power source. Therefore, if a well site does not have an appropriate power outlet, a generator is required. The thickness gage operates from either a power outlet or re-chargeable battery pack.

The first order of business at a well site is to select the location for the transducers on the discharge pipe. As far as possible, conventional rules are followed for selecting a section of pipe with a measurable flow profile. The Compliance Field Unit uses a Mylar template which wraps around a pipe and is scaled lengthwise along the edge such that the pipe circumference may be read in feet to hundredths. The thickness of the pipe is determined by averaging thickness-gage readings on either side of the pipe in the general areas that the transducers will be placed. The Comparagage provides readings in thousandths of inches. The inside diameter and the average thickness are then inserted into the following formula for transducer spacing on carbon-steel pipes:

$$TS = .99\ (\bar{t}) + .4375\ (ID)$$

where TS is the spacing in inches (rounded to the nearest hundredth), $\bar{t}$ is the average thickness in thousandths of inches, and ID is the inside diameter determined to hundredths of inches.

With the template still in place around the pipe, another scale along the bottom of the template is read in inches, and a mark made on the pipe corresponding to the transducer-spacing formula result. This will be the location of one transducer, the inside edge of which will be aligned at this point. Halving the circumference provides a point along the edge of the template 180 degrees around the pipe for the location of the other transducer (fig. 4). In general, the transducers are mounted in a plane along the pipe axis that is oriented between 45 degrees and 90 degrees from the top of the pipe. The surface of the pipe where the transducers will be mounted should be cleaned and corrosion and loose paint removed. This helps insure a good contact and signal transmission.

Before mounting, the transducers are zeroed in the "face-to-face" position per the manufacturer's instructions. They are then affixed to the pipe and held in place with nylon-web backpack straps that have snap-together buckles which tighten firmly. Sonic-coupling compound must be applied to the transducer faces for both zeroing and mounting. Ultragel II,

[2] In order to obtain additional information on the flowmeter's installation, operation, theory, and troubleshooting, refer to "Series 480 Clamp-On Flowmeter Instruction Manual", 480 IM-4A, 23 January 1984.

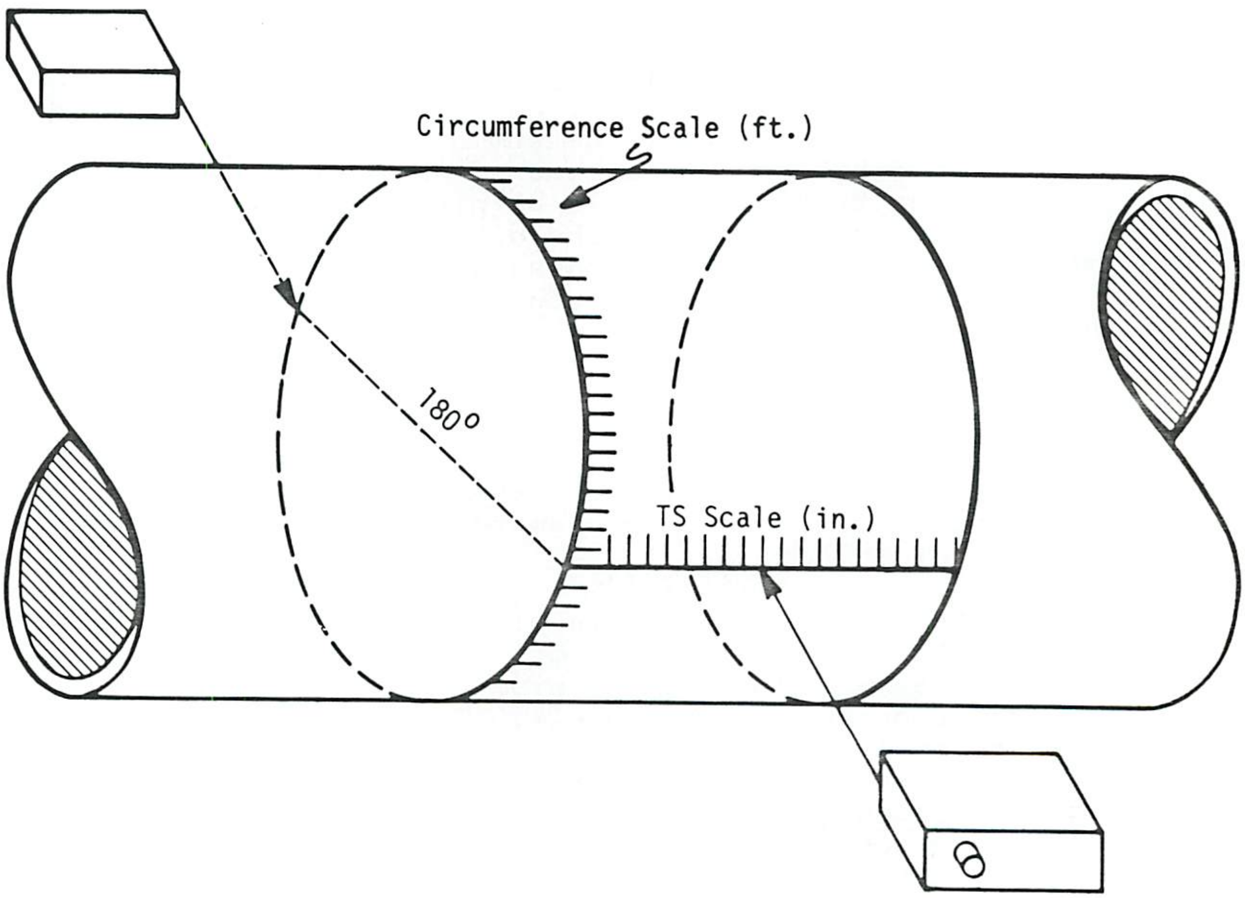


Figure 4.--Locating transducers on discharge pipe.

manufactured by Echo Ultrasound, Inc., of Lewistown, Pennsylvania, has been used for these purposes.

As operation commences, the transducer-spacing index dial must be set to correspond to the V_{TL} readout described earlier. This is most efficiently accomplished by rotating the dial until the lamp next to the dial flickers. If the receive-signal amplitude (V_{ALC}) is too low (less than about 2.7 volts), this adjustment can't be made and no flow readings are possible. The V_{ALC} can usually be increased by more sonic-coupling compound applied to the transducer faces, scraping the pipe at the contact, and even pounding on the pipe to loosen scale inside that may be impeding the signal. Entrained air and a less than full pipe will impede the signal and may not be controllable.

Once the transducer-spacing index dial has been set, flow readings are made and analog functions recorded. The digital-display readings flash regularly, and an average value is estimated and inserted into the following formula:

$$Q = \text{Average Units} \times \text{ADWR Coefficient}$$

where Q is the flow rate in gallons per minute, and the ADWR coefficient is the ratio of inside-pipe areas of the pipe being tested and the pipe for which the scale module has been programmed.

To demonstrate calculation of the ADWR coefficient, the 6.625CS.231 and 8.625CS.231 scale modules (hereafter referred to as the six-inch and the eight-inch modules) have been programmed for pipe areas of 29.83 and 52.33 square inches, respectively. Assuming the eight-inch module was being used on a pipe with an inside area of 115.75 square inches, then

$$\begin{aligned}\text{ADWR Coefficient} &= 115.75 \div 52.33 \\ &= 2.212.\end{aligned}$$

The mechanical totalizer is used for more precise average flow-rate readings, generally using a five-minute run. The totalizer reading is inserted into the following formula:

$$Q = \frac{\text{Totalizer Units} \times 60 \times \text{ADWR Coefficient}}{\text{Total Seconds in Timing}}$$

where Q is the flow rate in gallons per minute.

LABORATORY TEST RESULTS

The ADWR method has been tested in two laboratories where controlled flows could be maintained and adequate comparisons could be made with the mechanical-totalizer output and other functions of the flowmeter. The first testing was at the U.S. Department of Agriculture's Water Conservation Laboratory in Phoenix on May 16, 1986. The laboratory was set up to sustain and measure flows in a 12.83-inch outside diameter, .317-inch thick, carbon-steel pipe, as measured by ADWR personnel at the location of transducer placements. The laboratory is equipped with a tank which monitors the weight of water discharged into it over time. The unit weight of water is determined before a test run using measurements of total dissolved solids and temperature. Long-term tests are possible because the tank can be purged while receiving discharge. According to Dr. John Replogle, Laboratory Research Leader for Irrigation and Hydraulics, this system has an accuracy rating of ±.6 percent of actual flow. Depending on the flow rate, measurements were made based on timings for 10,000 to 30,000 pounds of water entering the tank.

The initial test runs were with the six-inch module, and were not considered successful. At laboratory-determined flow rates of 2987, 1647 and 1048 gallons per minute, computed rates were less by 83, 92 and 94 gallons per minute, respectively. It is not understood why this occurred because all readings otherwise seemed normal. However, the V_{TL} was approximately 12 volts, which is about the maximum setting for the transducer-spacing index dial, and there may have been an adjustment problem.

The next tests were with the eight-inch module. The percentage deviations of the calculated flow rates to the laboratory flow rates ranged from +1.7 percent at 1,034 gallons per minute to -.2 percent at 2,876 gallons per minute. The test results are presented in Table 1. The table also includes one entry for the six-inch module, which received one more trial following the eight-inch module tests (time constraints prohibited more tests). No explanation is here offered to account for the 1 gallon per minute difference between the readings at the 2,876 gallons per minute laboratory flow rate. However, the V_{TL} was set at about 12.2 volts rather than 12 volts, as it had been for the previous tests on the six-inch module.

Testing was performed at the Foundation for Cross-Connection Control and Hydraulic Research laboratory in Glendale, California, on June 27, 1986. Here are facilities to run tests on nominal pipe sizes of six, eight, and ten inches. The laboratory monitors flow rates with a mercury manometer attached to a venturi meter installed in a sixteen-inch pipe that distributes flow to the other pipes. The

Table 1--Results of tests of the ADWR method at U.S.D.A. Water Conservation Laboratory May 16, 1986

Scale module	Pipe area (in.^{2})	Pipe thick. (in.)	Lab Q (g.p.m.)	ADWR Q (g.p.m.)	(%)	V_{ALC} (volts)	V_{OF} (volts)	V_{TL}[a] (volts)	TS[b] (in.)	ADWR coef.)
Eight-inch	116.90	.317	1,034	1,052	+1.7	5.5	[c]7.1	9.1	5.90	2.234
Do	116.90	.317	1,456	1,466	+ .7	5.4	1.1	9.1	5.90	2.234
Do	116.90	.317	1,459	1,473	+1.0	nr	nr	nr	5.90	2.234
Do	116.90	.317	2,879	2,865	- .5	5.4	2.0	9.1	5.90	2.234
Do	116.90	.317	2,876	2,869	- .2	5.4	2.0	9.1	5.90	2.234
Six-inch	116.90	.317	2,876	2,875	.0	5.4	2.0	12.2	5.90	3.919

nr = not recorded

[a] At this time, the V_{TL} reading was being read from the transducer-spacing index dial instead of the more precise analog readout.

[b] The transducer-spacing formula used here differed slightly from the final form, which would have yielded 5.64 inches. It is estimated that the .26-inch increase in spread could have caused the apparent flow rate to increase about .3 percent. No adjustment, however, has been made in the flow-rate data, given the hypothetical nature of the small effect.

[c] The 7.1 volt reading was in the low-flow mode. It may be interpreted as indicating the actual flow velocity to be 71% of 4 feet per second. Considering the inside area of the pipe, this indicates a flow rate of 1,035 gallons per minute. This value can be used as a check on the flow rate determined from the totalizer. In the high-flow mode, the voltage indicates a percentage of 40 feet per second (e.g. 1.1 volts = 11% of 40 feet per second, or 4.4 feet per second).

accuracy of the system is estimated to be ±1 percent, although this is not precisely known according to Mr. Paul Schwartz, Chief Engineer. Normally, the laboratory measures pressure differences across in-line devices such as back-flow preventors. It was decided to run three-minute totalizer tests because water in the laboratory was not recycled but discharged into a reservoir draining into the Los Angeles River.

The initial set-up was with the six-inch module on a 6.68-inch outside diameter, .298-inch thick, carbon-steel pipe. At laboratory flow rates of 500, 753, and 1008 gallons per minute, computed rates were under by 10, 24 and 50 gallons per minute, respectively. All functions seemed normal, and there was no apparent explanation why the differences in rates were increasing logarithmically. Attempts to remedy the situation failed. Readings with the eight-inch module were attempted before realizing that the diameter of the pipe was too small for proper V_{TL} and transducer-spacing index setting. Time constraints dictated that the other pipe sizes be tested.

Successful tests with both scale modules were conducted on a 8.63-inch outside diameter, .248-inch thick, carbon-steel pipe. With the six-inch module, the percentage deviations of the calculated flow rates to the laboratory flow rates ranged from -2.3 percent at 574 gallons per minute to +.9 percent at 2,029 gallons per minute. The percentage deviations for the eight-inch module ranged from -1.4 percent at 501 gallons per minute to +.4 percent at 1,494 gallons per minute.

Problems were again encountered using the six-inch module on a 10.81-inch outside diameter, .355-inch thick, carbon-steel pipe. Again, undercomputing was occurring, but the percentage deviations were decreasing as flow rate was increasing. Several things were tried to isolate and remedy the problem including various transducer locations along and around the pipe. The resolution apparently occurred when the downstream and upstream transducers were detached from their respective cables and interchanged, even though the pre-interchange configuration had been successful on the eight-inch pipe. With apparently good readings being made, the percentage deviations from the six-inch module ranged from +.9 percent at 1,002 gallons per minute to -1.7 percent at 2,023 gallons per minute, and for the eight-inch module from +6.4 percent at 501 gallons per minute to -1.4 percent at 2,039 gallons per minute. The data from successful test runs are presented in Table 2. Lack of time prohibited any more testing.

Figures 5, 6, and 7 are plots of the test measurement deviations against the laboratory flow rates for each laboratory pipe. Each plot displays an arbitrary 2-percent envelope

Table 2--Results of tests of the ADWR method at the Foundation for Cross-Connection Control and Hydraulic Research June 27, 1986.

Scale module	Pipe area (in.^{2})	Pipe thick. (in.)	Lab Q (g.p.m.)	ADWR Q (g.p.m.)	(%)	V_{ALC} (volts)	V_{OF} (volts)	V_{TL}[a] (volts)	TS (in.)	ADWR coef.
Six-inch	51.91	.248	574	561	-2.3	5.7	1.0	8.0	3.80	1.740
Do	51.91	.248	1,002	995	- .7	5.7	1.6	8.0	3.80	1.740
Do	51.91	.248	1,494	1,497	+ .2	5.7	2.3	8.0	3.80	1.740
Do	51.91	.248	2,029	2,047	+ .9	5.7	3.1	8.0	3.80	1.740
Eight-inch	51.91	.248	501	494	-1.4	5.9	0.9	nr	3.80	.992
Do	51.91	.248	1,001	995	- .6	5.9	1.6	nr	3.80	.992
Do	51.91	.248	1,494	1,500	+ .4	5.9	2.3	nr	3.80	.992
Do	51.91	.248	2,010	2,012	+ .1	5.9	3.1	nr	3.80	.992
Six-inch	80.11	.355	534	534	.0	5.3	0.55	nr	4.77	2.686
Do	80.11	.355	1,002	1,011	+ .9	5.2	1.0	nr	4.77	2.686
Do	80.11	.355	1,507	1,497	- .7	5.2	1.55	nr	4.77	2.686
Do	80.11	.355	2,023	1,988	-1.7	5.1	2.0	nr	4.77	2.686
Eight-inch	80.11	.355	501	533	+6.4	5.1	0.6	7.5	4.77	1.531
Do	80.11	.355	1,008	1,020	+1.2	5.1	1.1	7.5	4.77	1.531
Do	80.11	.355	1,507	1,494	- .9	5.1	1.6	7.5	4.77	1.531
Do	80.11	.355	2,039	2,010	-1.4	5.1	2.0	7.5	4.77	1.531

nr = not recorded

[a] Reading from transducer-spacing index dial.

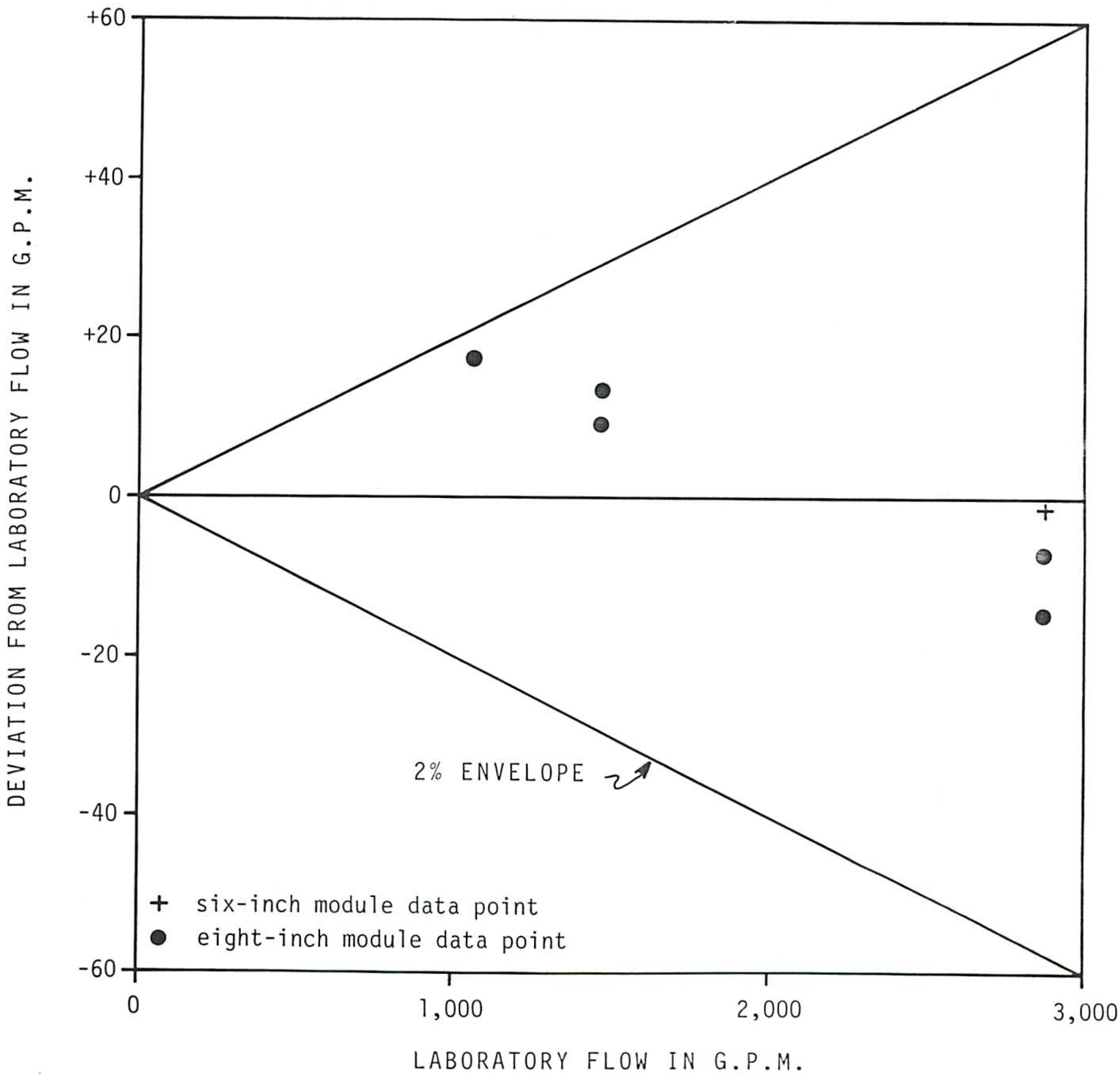


Figure 5.--Deviations of ADWR-method flows from laboratory flows in 12.83-in. carbon-steel pipe May 16, 1986.

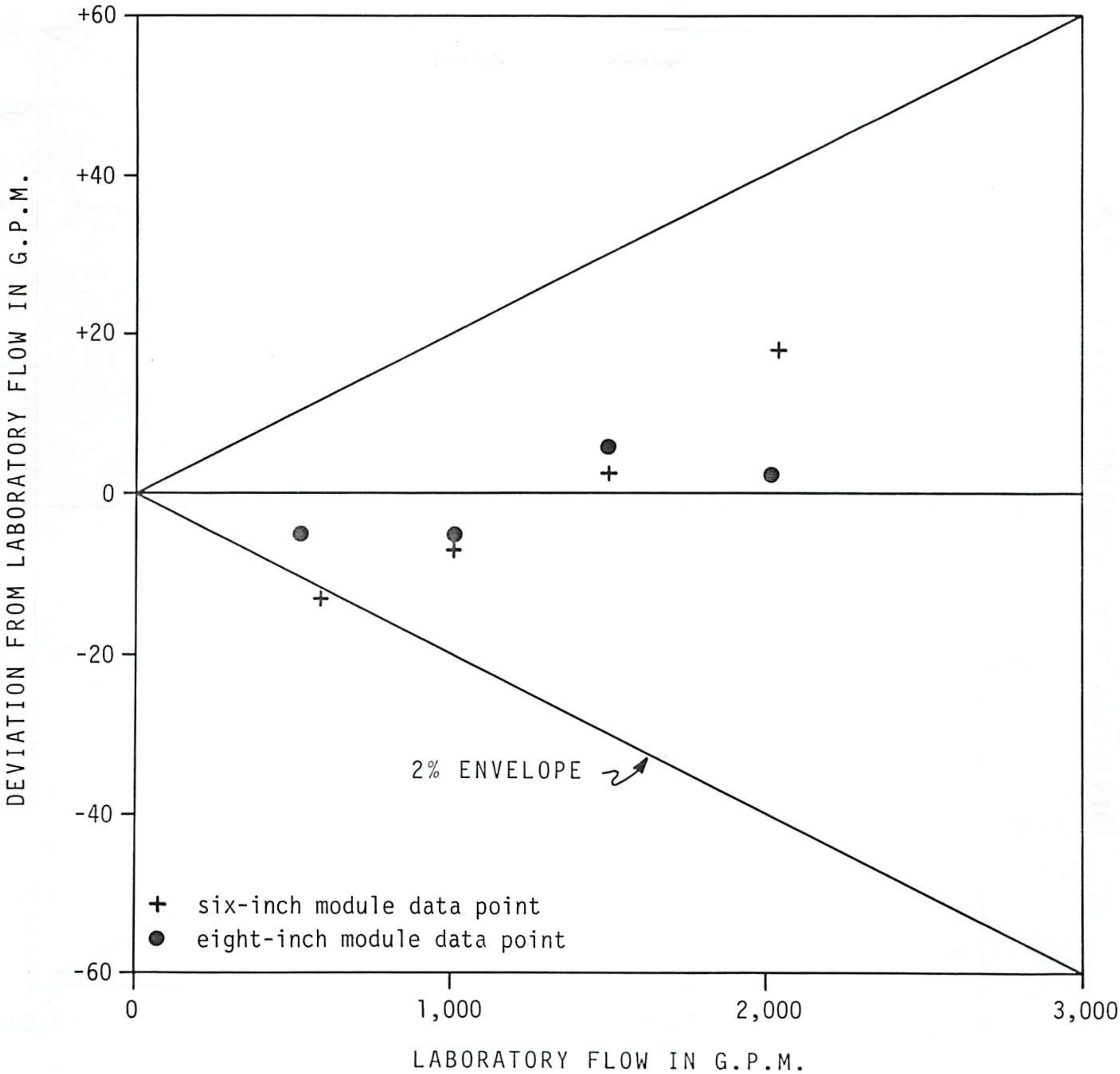


Figure 6.--Deviations of ADWR-method flows from laboratory flows in 8.63-in. carbon-steel pipe June 27, 1986.

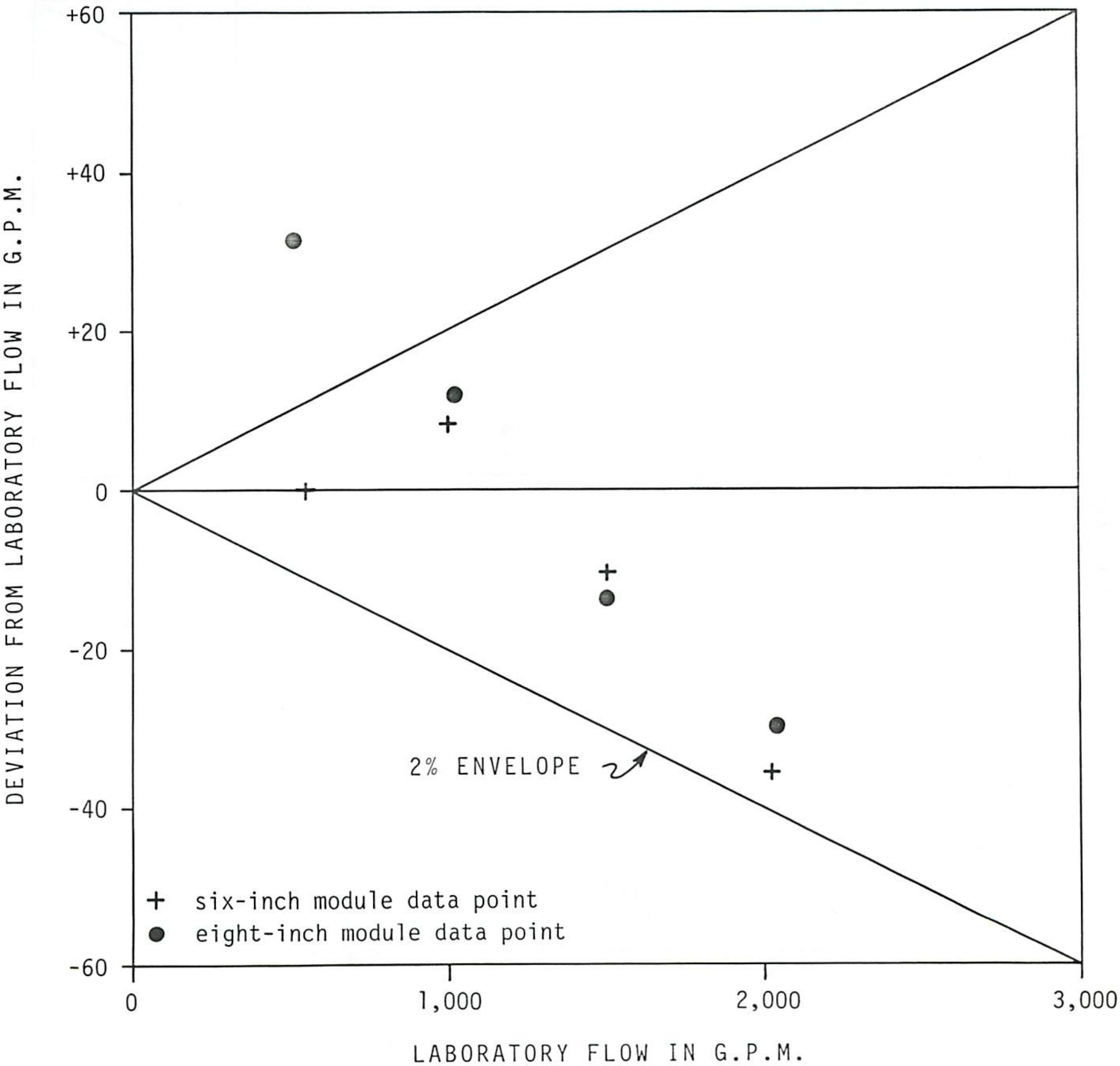


Figure 7.--Deviations of ADWR-method flows from laboratory flows in 10.81-in. carbon-steel pipe June 27, 1986.

for comparison purposes. Data points inside the envelope indicate agreement between laboratory and calculated flow rates within ±2 percent.

There appear to be definite trends in the figures, but the relatively few number of data points precludes detailed assessment. The trends may be related to the laboratory equipment, the flowmeter, observers, or combinations of all three. For instance, in figure 7, there is one highly anomalous data point, and there is an apparent trend of increasing percentage deviations for both scale modules as the flow rates increase. The flow rate in the ten-inch pipe was controlled by a sixteen-inch gate valve, and there was considerable pipe vibration which increased as the flow rate increased. The mercury-manometer readings were very "jittery." More extensive data collection under controlled conditions would be needed to resolve these issues. In figures 6 and 7, one definite trend appears to be high correspondence between the responses of the two scale modules at various flow rates.

APPLICATION LIMITATIONS AND RELATED CONSIDERATIONS

Experience using the ADWR method with the ultrasonic flowmeter has been limited. However, some indications of the range of use and limitations are apparent. Some of these relate strictly to the equipment belonging to the Department. Some limitations are environmental factors which would probably affect similar equipment. No inferences should be drawn from the following discussion about the behavior of the equipment when used according to the manufacturer's directions.

Field data (Appendix B) suggest that the measurable pipe-diameter range for the six-inch module is from about six inches nominal to about twelve inches nominal, and that of the eight-inch module, from about eight inches nominal to fifteen inches nominal. Based on what is believed known about the behavior of the flowmeter using the ADWR method, the ranges are theoretically 5.14 inches inside diameter (I.D.) to 12.33 inches I.D., and 6.80 inches I.D. to 16.33 inches I.D., respectively. Pipe thickness does not appear to be important, at least in the range from about one-tenth inch to one-half inch. It is possible that V_{TL} is actually proportional to path length (a function also of thickness) rather than inside diameter, which would slightly reduce the ranges of measurable sizes, but more information on this is needed.

It was noted by the field crews during the early spring 1986 data collection that the computer needed warm-up in the morning. It sometimes took several minutes to zero the transducers, and at times took from one-quarter to one-half hour to begin receiving readings in the operate mode in the early morning. As the heat increased to summer levels, it again became difficult to get readings, with the computer going into fault frequently, and interrupting totalizing runs. In general, the unit is no longer used when ambient air temperature is more than about 100°F and temperature cannot otherwise be controlled.

Already described in the section on laboratory test results is the intermittent under-registration of flow rates by the flowmeter. This problem may be confined to the six-inch module, but this is not certain. It may be an electronic short circuit. A review of the data in Appendix B suggests that it also may have occurred at times in the field, where the calculated flow rates were compared with those of in-line meters.

Because the ultrasonic flowmeter depends on a measurable flow profile, care must be taken to limit effects of sources of "turbulence" in pipes. These sources include valves, reductions, expansions, in-line devices, and elbows. In some cases where turbulence is unavoidable, it may be possible to average several readings around a pipe section by moving the transducers. When forced to set the transducers downstream and close to an elbow, apparently "good" readings have been obtained by setting the transducers in the geometric plane defined by the elbow.

Another problem has been the inability to use the flowmeter on some irrigation wells. Many irrigation wells have open discharge pipes which allow exposure of inside-pipe surfaces to the atmosphere when the wells are turned off. Long periods of such exposure to a pipe is believed to result in a corrosion problem whereby the receive-signal amplitude (V_{ALC}) is impeded. Remedies, such as pounding on the pipe, are sometimes ineffective in increasing the strength of the V_{ALC}.

The ADWR method relies on the operator's ability to obtain a representative average for the pipe thickness. This is important because the thickness value impacts both the transducer spacing (although only slightly) and the inside-pipe area calculation. It sometimes requires effort to get appropriate readings with the thickness gage the Department owns, partly because the face of the transducer is flat and pipe surfaces are curved. Care must be taken to obtain an average pipe thickness.

Finally, the transducer-spacing formula is based on the assumption that the sonic velocity of water is constant at 1,500 meters per second. In actuality, the sonic velocity of water at 25°C is 1,498 meters per second, and that of water at 32°C is 1,504 meters per second. Indeed, the sonic velocity of water may be assumed to be constant at temperatures within this range or outside this range within a few degrees Celcius. However, the transducer-spacing formula may not apply when measuring flows for very hot water or very cold water.

CONCLUSIONS

The laboratory test data indicate that use of the ADWR method with the Series 480 Clamp-On Flowmeter yields accurate results. At this stage of testing, the precise accuracy and related variables cannot be totally characterized. However, confidence within ±2 percent for eight to twelve-inch nominal carbon-steel pipes with flow rates in the range from about 500 to 3,000 gallons per minute is warranted. Because of the problem with the six-inch scale module, additional analysis of laboratory and field data is being conducted to determine if it is possible to detect under-registration of flow rate in the field when output functions otherwise appear normal with this particular module.

Additional laboratory testing is needed to quantify accuracy across the theoretical ranges of pipe diameter and thickness that the scale modules can measure. Applicability of the ADWR method to other pipe materials should also be demonstrated in the laboratory. These materials include cast iron, aluminum, and plastics.

The acquisition of additional equipment would expand the range of measurable pipe sizes. For instance, a scale module in the three or four-inch range with matching transducers would allow measurement of smaller pressurized public supply and industrial installations. Any such scale module should be laboratory tested with an appropriate transducer-spacing formula.

Used with the ADWR method, the Series 480 Clamp-On Flowmeter allows Arizona Department of Water Resources' personnel to collect discharge data on pressurized well systems without system shutdown or otherwise time-consuming and potentially hazardous procedures being undertaken. Since pipe invasion is not required and set-up is relatively easy, measurements at several system locations and around the pipe at a single location are possible where questions of excessive turbulence exist. As experience is gained in using the equipment, it may even become an effective diagnositc tool in identifying causes for in-line flowmeter under-registration or over-registration of flow.

APPENDIX A

DERIVATION OF TRANSDUCER-SPACING FORMULA FOR CARBON-STEEL PIPES

A transient-time ultrasonic flowmeter basically operates with a transducer sending a signal beam (actually a series of pulses) into the pipe wall. The beam is refracted by an amount depending on the angle of injection and the speed of sound (sonic velocity) in the pipe material. The beam passes into the liquid inside the pipe, where it is refracted again according to the angle of entry and the sonic velocity of the liquid. Another refraction occurs as the beam passes through the opposite pipe wall and is received by the second transducer. The process is then reversed when the second transducer does the sending and the first transducer does the receiving. The travel-time differential between the first signal and the second signal is proportional to the flow velocity of the liquid, which the flow computer translates into appropriate units. In order to obtain a proper flow velocity, the transducers must not only be oriented diametrically, but must also be offset along the pipe for the optimum beam path. This offset is a function of the optimum beam path angles in the pipe and liquid, and the pipe thickness and diameter. For the purposes at hand, water is the only liquid of interest, and its sonic velocity is assumed to be constant at approximately 1,500 meters per second. The general equation for the transducer spacing then becomes

$$\text{Tan } A\,(t_1 + t_2) + \text{Tan } B\,(ID) = L$$

where A is the angle from normal of the sonic beam path through the pipe material; B is the angle from normal of the sonic beam path through the water; t_1 and t_2 are the pipe thicknesses at the respective transducer locations; ID is the inside diameter of the pipe; and L is the offset along the pipe between the points of signal injection and signal reception. (See fig. A-1.)

The points of signal injection and reception in the transducers are at this writing not known to the author. However, a spacing solution is still possible since a "shadow" of the optimum path can be solved by using the manufacturer's recommended spacing for a pipe of specified material and dimensions. The shadow path yields the same spacing solution as would the "real" solution if all information were known.

Using the 484 MT tracks for an 8.625-inch outside diameter carbon-steel pipe with a thickness of .231 inches, the manufacturer recommends placing the facing edge of one transducer at the "2" index mark on one track, and that of the other at the "6" index mark on the opposing track, if water flow is to be measured with the appropriate scale module. This configuration was laid out graphically by carefully drawing a cross-section of such a pipe and pinpointing the respective index marks. The offset between the transducer edges was then determined to be 3.80 inches.[1] Reasoning that all the angles would remain the same, the resultant line

[1] This may correspond to the identity L_T = 3.792 in. that is stamped on the side of the 8.625 CS.231 scale module.

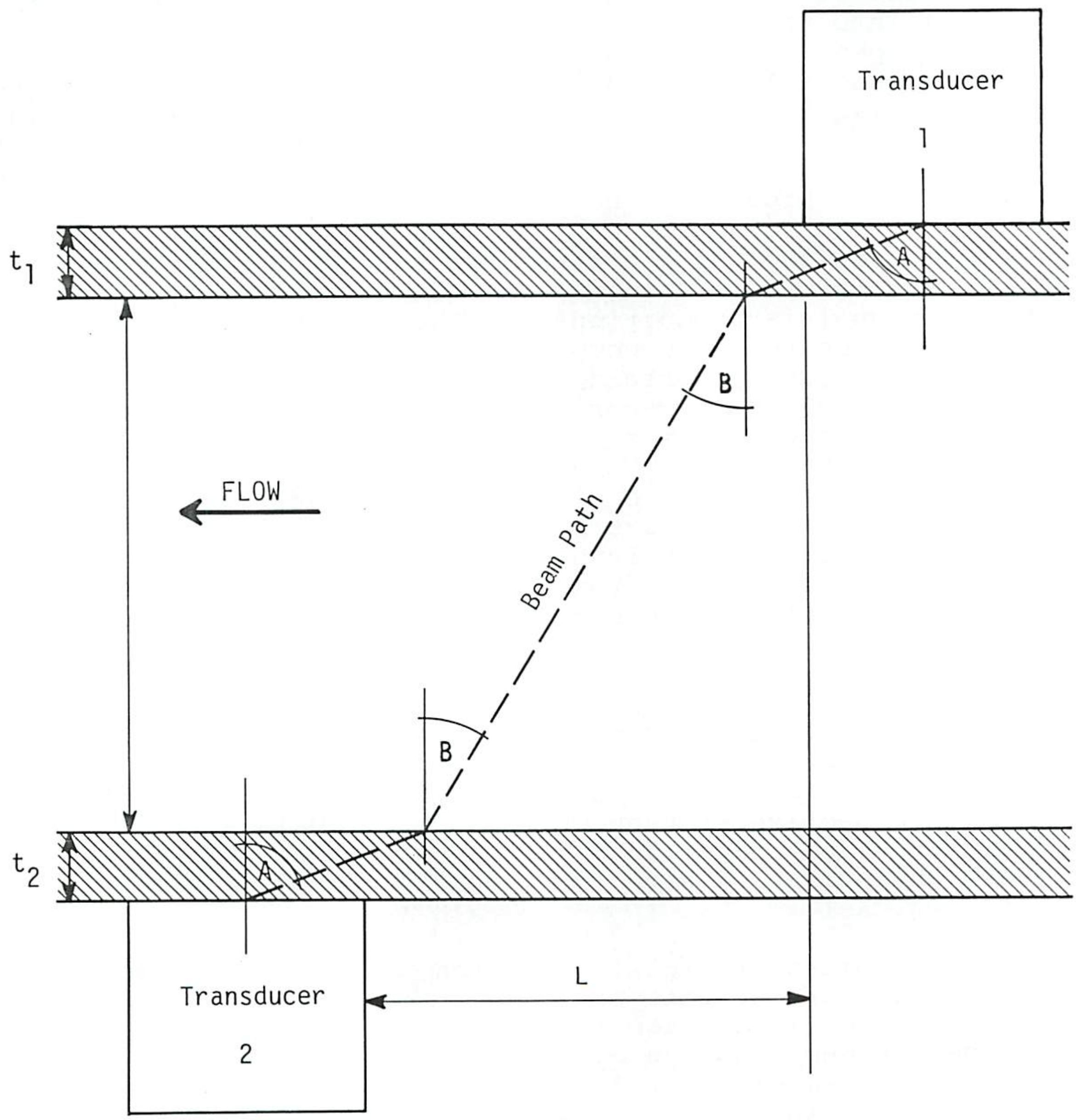


Figure A-1.

through the index marks was extended to where the edge of the moved transducer would be placed on a 12.625-inch outside diameter carbon-steel pipe with a .231 inch thickness. The resulting offset for this configuration was determined to be 5.55 inches. An algebraic solution was now possible for spacing the transducer edges on a carbon-steel pipe of any diameter and any thickness which produced V_{TL} readings within the ranges of the scale modules. Applying the previously described formula

$$\text{Tan } A = \frac{L_1 - \text{Tan } B\,(ID_1)}{(t_1 + t_2)}, \text{ and}$$

$$\frac{L_1 - \text{Tan } B\,(ID_1)}{(t_1 + t_2)}\,(t_1 + t_2) + \text{Tan } B\,(ID_2) = L_2$$

Simplifying and substituting yields

$$\begin{aligned} 3.80 - \text{Tan } B\,(8.163) + \text{Tan } B\,(12.163) &= 5.55 \\ \text{Tan } B &= .4375 \end{aligned}$$

Then $\text{Tan } A = \dfrac{3.80 - .4375\,(8.163)}{.462} = .4950$

In general, $t_1 \approx t_2$ and the values may be averaged such that the transducer-spacing formula can be written

$$\begin{aligned} TS &= .99\,(\bar{t}) + .4375\,(ID) \\ &\approx \bar{t} + .44\,(ID) \end{aligned}$$

where TS is the spacing in inches (rounded to the nearest hundredth), $\bar{t}$ is the average pipe thickness in thousandths of inches, and ID is the pipe inside diameter determined to hundredths of inches. Technically, the spacing result is only significant to tenths of inches.

APPENDIX B

FIELD DATA

Collected Field Data Using ADWR Method with Ultrasonic Transient-Time Flowmeter from April 4, 1986, to May 22, 1986.

Well	Date	In-line Meter (g.p.m.)	Pipe I.D. (in.)	Pipe thick. (in.)	Six-inch Module ADWR coef.	Six-inch Module ADWR Q (g.p.m.)	Six-inch Module Deviation[a] (%)	Eight-inch Module ADWR coef.	Eight-inch Module ADWR Q (g.p.m.)	Eight-inch Module Deviation[a] (%)	Analog Readings V_{TL} (volts)	Analog Readings V_{OF} (volts)	Analog Readings V_{ALC} (volts)
1	4-04-86	906	10.37	.225	2.831	963	6.3				10.75	1.0	4.3
		908						1.614	956	5.3	8.0	1.0	4.4
2	4-04-86	2256	12.05	.374	3.823	2236	-1.0				11.8	1.6	3.8
		2258						2.179	2234	-1.0	8.8	1.6	4.2
3	4-04-86	2189	12.32	.239	3.998	2252	2.9				11.8	1.55	5.45
		2200						2.279	2194	-0.3	8.8	1.55	5.45
4	4-08-86	1019	8.05	.326	1.706	1084	6.4				7.9	1.9	4.4
		1013						.973	1028	1.5	6.0	1.7	4.85
5	4-16-86	442	8.02	.346	1.693	445	0.7				7.8	[b]7.8	5.5
		456						.965	433	-3.9	5.8	[b]7.8	5.15
6	4-10-86	424	8.17	.322	1.757	406	-4.2				7.9	[b]6.4	5.6
		428						1.002	398	-7.0	6.0	[b]6.5	5.5
7	4-08-86	455	6.27	.244	1.036	437	-3.9				6.2	1.3	5.7
8	4-16-86	527	10.13	.378	2.704	516	-2.1				9.9	[b]5.5	5.25
		517						1.541	500	-3.3	7.4	[b]5.0	3.8
9	4-16-86	387	8.06	.327	1.710	394	1.8				8.0	[b]6.0	5.5
		393						.975	390	- .8	6.0	[b]6.0	5.5

[a] Deviation of ADWR Q with respect to in-line meter Q.

[b] Low-flow mode.

Collected Field Data Using ADWR Method with Ultrasonic Transient-Time Flowmeter from April 4, 1986, to May 22, 1986.

					Six-inch Module			Eight-inch Module			Analog Readings		
Well	Date	In-line Meter (g.p.m.)	Pipe I.D. (in.)	Pipe thick. (in.)	ADWR coef.	ADWR Q (g.p.m.)	Deviation[a] (%)	ADWR coef.	ADWR Q (g.p.m.)	Deviation[a] (%)	V_{TL} (	V_{OF} volts	V_{ALC})
10	4-15-86	2803	12.28	.452	3.968	2823	0.7				12.2	2.0	4.3
		2798						2.262	2731	-2.4	9.0	1.95	4.8
11	4-15-86	2119	12.09	.379	3.850	1900	-10.3				12.2	1.45	4.7
		2119						2.190	1830	-13.6	9.0	1.3	4.6
12	4-21-86	2196	10.17	.300	2.723	2200	1.1				10.0	2.2	3.9
		2199						1.552	2176	- 1.0	7.4	2.2	4.6
13	4-22-86	971	8.28	.214	1.806	1066	9.8				7.9	1.6	4.6
		975						1.029	1047	7.4	5.8	1.8	4.9
14	4-21-86	876	10.01	.382	2.636	845	-4.0				9.7	[b]8.5	5.2
		873						1.503	842	-3.5	7.5	[b]8.5	5.2
15	4-25-86	887	10.08	.366	2.674	910	2.6				10.1	1.0	5.0
		894						1.524	884	-1.1	7.5	1.0	4.5
16	4-25-86	1125	8.00	.335	1.685	1018	-9.5				8.1	1.7	5.0
		1124						.961	1022	-9.1	6.1	1.7	5.1
17	4-18-86	421	10.35	.269	2.822	482	14.5				10.0	[b]6.0	4.3
		421						1.608	471	11.9	7.4	[b]4.4	4.0
18	4-18-86	739	6.14	.330	.993	708	-4.2				6.2	1.75	5.3
		739											
19	4-18-86	1146	8.06	.327	1.710	1108	-3.3				8.1	1.8	5.6
		1146						.975	1108	-3.3	6.0	1.7	5.6
20	4-18-86	1037	8.03	.338	1.698	1097	5.8				8.0	1.6	5.8
		1037						.968	1019	-1.7	5.9	1.7	5.8

Collected Field Data Using ADWR Method with Ultrasonic Transient-Time Flowmeter from April 4, 1986, to May 22, 1986.

Well	Date	In-line Meter (g.p.m.)	Pipe I.D. (in.)	Pipe thick. (in.)	Six-inch Module ADWR coef.	Six-inch Module ADWR Q (g.p.m.)	Six-inch Module Deviation[a] (%)	Eight-inch Module ADWR coef.	Eight-inch Module ADWR Q (g.p.m.)	Eight-inch Module Deviation[a] (%)	Analog Readings V_{TL} (volts)	Analog Readings V_{OF} (volts)	Analog Readings V_{ALC} (volts)
21	4-18-86	900	6.18	.288	1.007	895	-0.5				6.0	2.4	3.8
22	4-21-86	784	6.22	.269	1.019	850	8.4				6.1	2.2	3.9
23	4-18-86	1600	10.10	.376	2.685	1383	-13.6				10.1	1.45	5.05
		1601						1.530	1364	-14.8	7.6	1.45	5.1
24	4-21-86	430	6.17	.275	1.002	418	- 2.8				6.1	1.2	5.9
25	4-21-86	232	6.15	.287	.995	247	6.5				nr	nr	nr
26	5-08-86	1423	10.32	.248	2.801	1286	- 9.6				10.2	1.3	3.5
		1422						1.597	1268	-10.8	7.6	1.3	3.6
27	5-08-86	894	12.10	.350	3.855	889	- 0.6				12.0	[b]6.0	5.0
		907						2.197	869	- 4.2	9.1	[b]6.0	5.4
28	5-08-86	1137	10.01	.382	2.636	990	-12.9				10.1	1.05	4.9
		1156						1.503	956	-17.3	7.5	1.1	4.6
29	4-29-86	898	10.09	.359	2.682	792	-11.8				9.9	[b]7.7	2.4
		883						1.529	851	- 3.6	7.4	[b]7.5	2.3
30	4-29-86	1059	11.99	.406	3.784	1011	- 4.5				11.9	[b]7.2	2.7
		1059						2.157	1055	- 0.4	9.0	[b]8.5	2.9
31	5-07-86	598	8.17	.312	1.757	644	7.7				8.0	1.1	4.7
		598						1.002	646	8.0	5.9	1.05	5.4

nr = not recorded

Collected Field Data Using ADWR Method with Ultrasonic Transient-Time Flowmeter from April 4, 1986, to May 22, 1986.

					Six-inch Module			Eight-inch Module			Analog Readings		
Well	Date	In-line Meter (g.p.m.)	Pipe I.D. (in.)	Pipe thick. (in.)	ADWR coef.	ADWR Q (g.p.m.)	Deviation[a] (%)	ADWR coef.	ADWR Q (g.p.m.)	Deviation[a] (%)	V_{TL} (	V_{OF} volts	V_{ALC})
32	5-20-86	583	8.12	.295	1.736	615	5.5				8.0	1.05	5.1
		586						.990	538	- 8.2	6.0	[b]8.4	4.8
33	5-20-86	550	6.13	.276	.989	542	-1.5				6.1	1.5	5.5
		550											
34	5-20-86	729	8.06	.304	1.710	629	-13.7				8.1	1.3	5.45
		727						.975	705	- 3.0	6.1	1.2	5.4
35	5-22-86	855	8.00	.333	1.687	822	- 3.9				8.2	1.4	6.1
		859						.962	828	- 3.6	6.1	1.45	6.0
36	5-22-86	589	8.02	.327	1.692	547	- 7.1				8.1	1.0	5.25
		592						.964	542	- 8.4	6.0	1.0	5.65
37	5-22-86	575	8.01	.332	1.689	611	6.3				8.1	1.1	5.7
		575						.963	667	16.0	5.9	1.15	3.9
38	5-22-86	550	8.01	.328	1.689	487	-11.5				8.0	[b]7.8	5.3
		551						.963	479	-13.1	6.1	[b]7.5	4.0
39	5-22-86	682	7.98	.326	1.676	605	-11.3				8.0	1.1	5.1
		684						.955	592	-13.5	6.1	1.1	2.75
40	5-22-86	808	7.99	.341	1.680	765	- 5.3				7.9	1.35	5.85
		806						.958	752	- 6.7	5.9	1.35	5.9
41	5-22-86	645	8.14	.264	1.745	646	0.2				8.1	1.1	5.6
		646						.995	648	0.3	6.0	1.15	5.1
42	5-22-86	383	8.06	.306	1.710	406	6.0				8.0	[b]6.3	5.9
		385						.975	407	5.7	6.0	[b]6.3	5.1

Collected Field Data Using ADWR Method with Ultrasonic Transient-Time Flowmeter from April 4, 1986, to May 22, 1986.

Well	Date	In-line Meter (g.p.m.)	Pipe I.D. (in.)	Pipe thick. (in.)	Six-inch Module ADWR coef.	Six-inch Module ADWR Q (g.p.m.)	Six-inch Module Deviation[a] (%)	Eight-inch Module ADWR coef.	Eight-inch Module ADWR Q (g.p.m.)	Eight-inch Module Deviation[a] (%)	Analog Readings V_{TL} (volts)	Analog Readings V_{OF} (volts)	Analog Readings V_{ALC} (volts)
43	5-20-86	620	7.99	.338	1.683	555	-10.5				8.0	1.0	5.4
		617						.959	605	-1.9	6.0	1.0	5.3
44	5-21-86	396	8.14	.267	1.743	354	-10.6				7.8	[b]5.7	4.7
		393						.993	362	-7.9	5.9	[b]6.6	5.2
45	5-21-86	335	8.17	.248	1.757	377	12.5				8.0	[b]5.6	4.8
		336						1.002	360	7.1	6.1	[b]5.2	3.5
46	5-21-86	408	8.17	.272	1.757	475	16.4				7.6	[b]9.0	4.2
		404						1.002	457	13.1	5.9	[b]7.1	5.1
47	5-21-86	573	8.03	.322	1.696	584	1.9				8.0	1.05	5.25
		573						.967	584	1.9	6.0	1.05	5.3
48	5-21-86	360	8.04	.314	1.703	383	6.4				8.2	[b]6.1	4.8
		358						.971	374	4.5	6.0	[b]6.0	5.0
49	5-21-86	528	8.04	.314	1.703	548	3.9				8.1	1.0	4.2
		527						.971	555	5.3	6.2	1.0	5.0
50	4-21-86	468	6.19	.266	1.009	540	15.4				6.1	1.5	3.7
		469											
51	4-18-86	1496	10.07	.390	2.675	1387	- 7.3				10.0	1.5	5.3
		1497						1.525	1377	-8.0	7.5	1.4	5.2